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THE UNIVERSITY OF MICHIGAN

COLLEGE OF ENGINEERING
DEPARTMENT OF AEROSPACE ENGINEERING
HIGH ALTITUDE ENGINEERING LABORATORY

Ionospheric Characteristics from Altitude Variations of Positive Ion Densities

S. N. GHOSH

Under contract with:

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Scientific Report

IONOSPHERIC CHARACTERISTICS FROM ALTITUDE VARIATIONS OF POSITIVE ION DENSITIES

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ABSTRACT

Altitude variations of different types of positive ions in the ionosphere obtained from rocket-borne experiments, have supplemented the collective information of ions obtained from ground-based experiments and have given additional information of the ionized layers of the upper atmosphere. Among other conclusions it is shown that, whereas for O^+ and N_2^+, photoionization is important, greater numbers of O_2^+ and NO^+ ions are created by charge exchange or ion-atom interchange reactions from ions originally produced by solar rays. This conclusion is confirmed by the observed low densities of O^+ and N_2^+ ions at night. It is proposed that the conclusion can be settled conclusively by noting the variation of positive ion densities during a flare or at an eclipse.

Analysis of the data shows that at each level between 100 and 280 km the total rate of production of different types of positive ions by solar rays is approximately equal to their total loss rate. Since the lifetimes of ions are small, the steady state is reached within a short time when the divergence term becomes nearly equal to zero.

To understand the overall loss rates of positive ions in the ionosphere, the effective recombination coefficient of positive ions with electrons is defined in line with the effective electron recombination coefficient, and its values for various types of recombinations are given.

1. INTRODUCTION

For understanding the ionized layers of the upper atmosphere, one should consider the production of electrons, their loss and movements (diffusion and/ or drift). A first requirement for the formulation of their theory is a knowledge of electron density as a function of height. To have a detailed understanding of these layers, one should know in addition to the electron density distribution, the altitude variation of each constituent positive ion density. The latter information is now available from rocket-borne mass spectrometers and dispersive Doppler radio propagation experiments. It has supplemented the collective information of ions obtained from ground-based experiments and has enabled one to obtain additional information of the ionosphere.

A problem of considerable significance is to find out which of the positive ions present in the ionosphere is produced directly by solar rays and which ones by charge exchange or ion-atom interchange with neutral particles from ions originally produced by solar rays (corpuscular ionizing influence is small except at high altitudes or during periods of solar activity). The question can be answered by determining the density of positive ions in the absence of solar rays. For example, if they are produced by EUV and X-rays emanated from the sun, the ion density would then vary directly with solar rays, i.e., with the 11-year solar cycle, the zenith angle and solar conditions. Observations of the change of positive ion density with the sun's position, namely, the rapid density decrease at night, would therefore confirm their production by solar photons. Doubtless this issue can be settled conclusively by noting the increase of the positive ion density during a flare, or from its decreasing during an eclipse.

This and other problems arise concerning the ionosphere. Based upon the recent rocket measurements of positive ion density in the upper atmosphere and laboratory measurements of rate coefficients of reactions involving atmospheric constituents, an attempt has been made to elucidate the characteristics of the ionosphere at daytime during a period of minimum solar activity.

2. MASS-SPECTROMETRIC ANALYSIS OF POSITIVE IONS

Using rocket-borne mass spectrometers and dispersive Doppler radio propagation experiments during the last period of solar minimum activity, daytime altitude variations of positive ions* between an altitude of 100-280 km averaged from observations made by different investigators are shown in Fig. 1. For certain ions, to obtain distributions for the whole altitude range, the observed curves have been extrapolated and are shown by broken curves. These observations show that during daytime, O^+ is the major positive ion above 180 km and between 100-160 km, O_2^+ and NO^+ ions predominate. N_2^+ is a minor ion in the ionosphere (Johnson, 1966 and others). The electron density is assumed to be the sum of the individual positive ion densities (Fig. 1).

The observed positive ion density distributions at night for the same minimum solar activity period (Holmes, et al., 1965) are also shown in Fig. 1. Note the low densities of O^+ and N_2^+ ions and the rapid fall of O^+ ions from 230 km with the decreasing altitude at night.

*Concentrations of ions at solar maximum may be higher by one order (Istomin, 1965).

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3. PRODUCTION OF POSITIVE IONS

PHOTOPRODUCTION OF POSITIVE IONS

Photoproduction rates of O^+, O_2^+, and N_2^+ ions in the upper atmosphere for overhead sun obtained by Hinteregger, et al. (1965) are shown in Figs. 2-4. The NO^+ ion production rate (Fig. 5) by Lyman-α (having a flux of 2.7×10^{11} photons/cm^2 sec outside the earth's atmosphere) is calculated* after assuming the altitude distribution of NO given by Ghosh (1966) and its ionization cross section as 2×10^{-18} cm^2. Before ionizing NO, Lyman-α radiations are partially absorbed by O_2 (absorption coefficient = 1×10^{-20} cm^2 at Lyman-α). The photoproduction rate of N^+ (Fig. 6) is obtained from that of O^+ given by Hinteregger and the ratio of photoionization cross sections of O and N atoms given by Dalgarno, et al. (1960).

The spectral ranges which contribute significantly for the production of ions at different altitudes are given in Table 1.

Table 1 shows that as solar rays penetrate the atmosphere, O^+, O_2^+, and N^+ ions are produced significantly by utilizing 700-350A radiations. Then, on penetrating deeper between 100-160 km, two spectral ranges, between the threshold first ionization wavelength and 700A, and 300-1A are mainly utilized for additional production of these ions.

POSITIVE ION PRODUCTION BY CHARGE EXCHANGE AND ION-ATOM INTERCHANGE

The dissociative recombination, charge exchange and ion-atom interchange reactions involving O^+, O_2^+, N_2^+, NO^+, and N^+ ions and atmospheric gases and their rate coefficients are given in Table 2. The altitude variations of the total rate of production of ions (by photons plus exchange of charge) and their total loss rate (by recombination, charge exchange or ion-atom interchange) for each ion are shown in Figs. 2-6. The production and loss rates are calculated by using the usual formula, namely, the rate is equal to the product of rate coefficients and concentrations of the reacting particles.

*The photoionization rate at an altitude z is calculated by using the well-known formula, namely

$$n(NO)_z Q N(h\nu)_z$$

where $n(NO)_z$ is the concentration of NO at an altitude z, Q its ionization cross section for 1216A and $N(h\nu)_z$ is the photon-flux for overhead sun.

TABLE 1

MAJOR RADIATIONS UTILIZED FOR PRODUCTION OF POSITIVE IONS

Positive Ion	Altitude Range (km)	Spectral Range (A)
	100-280	310-1
O^+	150-280	665-435
	100-140	911-732
	130-160	310-1
O_2^+	160-280	681-443
	100-160	1027-765
	100-150	355-1
N_2^+	150-280	659-355
	100-180	310-1
N^+	160-280	665-435
	110-180	852-732
NO^+	100-280	1216

TABLE 2

REACTIONS BETWEEN POSITIVE IONS AND ATMOSPHERIC GASES IN THE IONOSPHERE

Positive Ion	Reaction	Coefficient Used for Computation ($cm^3\ sec^{-1}$)
O^+	$O^+ + NO \rightarrow O_2^+ + N$	$4.6\times10^{-8} \exp(-4500/RT)$ (Goldan, et al., 1966)
	$O^+ + N_2 \rightarrow NO^+ + N$	$4.2\times10^{-12} \exp(-470/RT)$ (Danilov, 1966)
	$O^+ + O_2 \rightarrow O + O_2^+$	$8\times10^{-12}\ (1200/T)^{1/2}$
	$O^+ + NO \rightarrow O + NO^+$	$4.6\times10^{-8} \exp(-4500/RT)$ (Goldan, et al., 1966)
O_2^+	$O_2^+ + e \rightarrow O + O$	2.6×10^{-7} at 300°K and varies as $1/T$ (Whitten, et al., 1965)
	$O_2^+ + N_2 \rightarrow NO^+ + NO$	$7.5\times10^{-11}\ T^{1/2} \exp(-8500/RT)$*
	$O_2^+ + NO \rightarrow NO^+ + O_2$	$3\times10^{-7} \exp(-4500/RT)$**
	$O_2^+ + N \rightarrow NO^+ + O$	$2.9\times10^{-9} \exp(-1590/RT)$ (Goldan, et al., 1966)
N_2^+	$N_2^+ + e \rightarrow N + N$	7×10^{-7} at 300°K, varies as $1/T$ (Whitten, et al., 1965)
	$N_2^+ + N \rightarrow N_2 + N^+$	$4\times10^{-9} \exp(-3560/RT)$
	$N_2^+ + O_2 \rightarrow NO^+ + NO$ $\rightarrow N_2 + O_2^+$	2×10^{-10} (Whitten, et al., 1965)***
	$N_2^+ + O \rightarrow NO^+ + N$ $\rightarrow N_2 + O^+$	$1.0\times10^{-7} \exp(-3560/RT)$ (Ferguson, et al., 1965)***
	$N_2^+ + NO \rightarrow N_2 + NO^+$	5×10^{-10}
NO^+	$NO^+ + e \rightarrow N + O$	3.5×10^{-7} at 300°K, varies as $1/T$ (Whitten, et al., 1965)
N^+	$N^+ + NO \rightarrow NO^+ + N$	8×10^{-10} (Goldan, et al., 1966)
	$N^+ + O_2 \rightarrow NO^+ + O$ $\rightarrow N + O_2^+$	1×10^{-9} (Goldan, et al., 1966)***
	$N^+ + O \rightarrow N + O^+$	1×10^{-10}

*For this reaction, activation energy is large (Nicolet, 1965b).

**To reduce the loss rate of O_2^+ ions, the coefficient is assumed to have a value nearly equal to the lower limiting value given by Goldan, et al. (1966).

***Contribution to each reaction is assumed equal.

Ions, neutral particles, and electrons are assumed to be in thermal equilibrium and to have temperatures given by CIRA, 1965.*

Major production and loss reactions of positive ions at different altitude ranges are given in Table 3.

From the production and loss rates of different types of positive ions, certain conclusions can be made.

1. The above figures show that photoionization is important for the production of O^+, N_2^+, and N^+ ions. For O_2^+, a large number of ions is produced by a charge exchange or ion-atom interchange from O^+ ions originally created by photons. NO^+ ions are produced mainly by charge exchange or ion-atom interchange from O^+ ions produced by solar rays or from O_2^+ ions. Owing to the low ionization potential of NO (9.5 ev) and high NO^+ dissociation energy (9.4 or 10.6 ev), NO^+ ions do not undergo charge exchange or ion-atom interchange with atmospheric gases.

In conformity with the above conclusion the rocket-borne mass spectrometers showed low densities of O^+ and N_2^+ ions at night (Fig. 1). To decide conclusively that they are produced by solar rays, it is desired to determine their densities during a flare, or at an eclipse.

2. Unlike O_2^+ and NO^+ ions, N_2^+ do not disappear mainly by dissociative recombination with electrons, but by first forming NO^+ ions through the reaction

$$N_2^+ + O \rightarrow NO^+ + N$$

which then undergo dissociative recombination with electrons. The interchange process occurs for the whole altitude range 100-280 km. Whereas for O^+ and O_2^+ ions, major loss processes are ion-atom interchange with all atmospheric gases, N_2^+ ions react only with O atoms.

3. From Figs. 2-4 it appears that, within the accuracy of the coefficients of reactions, for each of O^+, N_2^+, and O_2^+ ions, the rate of production of ions at each level of the altitude range 100-280 km nearly balances the loss rate. On the other hand, for NO^+ ions, the production rate is very much greater than the loss rate (Fig. 5) and the reverse for N^+ ions (Fig. 6) (unless the coefficients of reactions are changed, the loss rates will not alter as they have been calculated from the observed ion and electron densities).

*Actually for the whole altitude range 100-280 km, they are not in thermal equilibrium (Thomas, 1966). However, in the absence of accurate information of the temperature variation of rate coefficients, thermal equilibrium between different particles of the ionosphere has been assumed.

TABLE 3

MAJOR PRODUCTION AND LOSS REACTIONS IN THE IONOSPHERE

Positive Ion	Production Process: Reaction	Production Process: Altitude (km)	Loss Process: Reaction	Loss Process: Altitude (km)
O^+	$O+h\nu \rightarrow O^+ + e$	Photoproduction is important throughout 100-280 km	$O^+ + N_2 \rightarrow NO^+ + N$	280-100
			$O^+ + NO \rightarrow O_2^+ + N$	250-175
			$O^+ + O_2 \rightarrow O + O_2^+$	175-100
N_2^+	$N_2 + h\nu \rightarrow N_2^+ + e$	Photoproduction is important throughout 100-280 km	$N_2^+ + O \rightarrow NO^+ + N$	280-100
O_2^+	$O_2 + h\nu \rightarrow O_2^+ + e$	100-160	$O_2^+ + e \rightarrow O + O$	280-220 and 120-100
	$O^+ + O_2 \rightarrow O_2^+ + O$	160-190	$O_2^+ + NO \rightarrow NO^+ + O_2$	280-130
	$O^+ + NO \rightarrow O_2^+ + N$	160-280	$O_2^+ + N_2 \rightarrow NO^+ + NO$	280-100
			$O_2^+ + N \rightarrow NO^+ + O$	280-100
NO^+	$N_2^+ + O \rightarrow NO^+ + N$	280-190	$NO^+ + e \rightarrow N + O$	280-100
	$O_2^+ + NO \rightarrow NO^+ + O_2$ $O_2^+ + N_2 \rightarrow NO^+ + NO$	280-120		
	$O_2^+ + N \rightarrow NO^+ + O$ $O^+ + N_2 \rightarrow NO^+ + N$	220-180		
N^+	$N + h\nu \rightarrow N^+ + e$	Photoproduction is important throughout 100-280 km	$N^+ + O_2 \rightarrow \begin{cases} O_2^+ + N \\ NO^+ + O \end{cases}$	280-100

Note: Owing to the uncertainties in the value of the cross section for $N_2 + h\nu \rightarrow N + N^+ + e$, the reaction is not considered (McElroy, 1967).

The inequality between these rates for N^+ ions cannot be resolved by postulating a new source of ionization, for example, high-energy particles from the sun because it is hardly possible that these particles will ionize N atoms alone, but not NO molecules having lower ionization potential.

4. Calculations show that at each level in the altitude range 100-280 km, the total rate of production of positive ions by solar rays is approximately equal to their total loss rate (Fig. 7), which is carried in the final stage by dissociative recombinations. Therefore

$$Q_1[O]n(h\nu_1) + Q_2[N_2]n(h\nu_2) + Q_3[O_2]n(h\nu_3) + Q_4[NO]n(h\nu_4) + Q_5[N]n(h\nu_5)$$

$$\doteqdot \alpha_{D_1}[N_2^+][e] + \alpha_{D_2}[O_2^+][e] + \alpha_{D_3}[NO^+][e]$$

where Q's are ionization cross sections by photons of frequencies ν's and α_D's are dissociative recombination coefficients of molecular ions with electrons.

Since the lifetimes of ions are small (Table 4),* the steady state is quickly reached. Using the continuity equation, we have then

$$0 = \frac{d\Sigma n_i^+}{dt} = \Sigma q_i - \Sigma L_i - \mathrm{div}\,(\Sigma n_i^+ w_i)$$

where q_i and L_i are the production and loss rates of positive ions of density n_i^+ and having vertical velocity w_i. Since Σq_i is nearly equal to ΣL_i the divergence term is approximately zero.

*Note that for N_2^+ and NO^+ ions, the lifetimes are nearly constant for the whole 100-280 km altitude range.

TABLE 4

LIFETIMES OF DIFFERENT POSITIVE IONS IN THE IONOSPHERE

Altitude (km)	Lifetimes (sec) of Positive Ions				
	O^+	O_2^+	N^+	N_2^+	NO^+
100	5.0×10^{-1}	3.8×10^{1}	1.0×10^{0}	5.0×10^{-1}	4.5×10^{1}
110	5.0×10^{-1}	1.9×10^{1}	1.0×10^{0}	4.8×10^{-1}	2.6×10^{1}
120	7.4×10^{-1}	2.2×10^{1}	1.0×10^{0}	4.7×10^{-1}	3.8×10^{1}
130	1.9×10^{0}	1.4×10^{1}	1.0×10^{0}	4.9×10^{-1}	8.2×10^{1}
140	4.7×10^{0}	6.9×10^{0}	1.0×10^{0}	4.4×10^{-1}	8.7×10^{1}
150	8.9×10^{0}	5.5×10^{0}	1.0×10^{0}	5.5×10^{-1}	9.5×10^{1}
160	1.5×10^{1}	4.5×10^{0}	9.7×10^{-1}	6.6×10^{-1}	9.3×10^{1}
170	2.2×10^{1}	4.2×10^{0}	1.0×10^{0}	7.2×10^{-1}	8.6×10^{1}
180	3.1×10^{1}	3.8×10^{0}	1.3×10^{0}	7.8×10^{-1}	7.6×10^{1}
190	4.6×10^{1}	3.7×10^{0}	2.1×10^{0}	8.2×10^{-1}	6.6×10^{1}
200	6.6×10^{1}	4.0×10^{0}	3.4×10^{0}	8.1×10^{-1}	5.4×10^{1}
220	1.3×10^{2}	7.2×10^{0}	7.8×10^{0}	8.4×10^{-1}	4.4×10^{1}
240	2.4×10^{2}	1.0×10^{1}	2.1×10^{1}	8.6×10^{-1}	3.8×10^{1}
250	3.5×10^{2}	1.1×10^{1}	3.3×10^{1}	8.7×10^{-1}	3.7×10^{1}
260	5.1×10^{2}	1.2×10^{1}	5.1×10^{1}	9.0×10^{-1}	4.4×10^{1}
280	1.4×10^{3}	1.2×10^{1}	1.2×10^{2}	9.3×10^{-1}	7.5×10^{1}

4. EFFECTIVE RECOMBINATION COEFFICIENT OF POSITIVE IONS

Before considering the effective recombination coefficient of positive ions, let us first consider it for free electrons. They may be lost by various processes, namely, by simple recombination with positive ions, the so-called radiative recombination, or by a complicated process for example, by attachment to neutral atoms to form negative ions and then their subsequent loss by ionic recombination with positive ions. However, whatever be the process of recombination, the electron decay can be written as if the net effect is a simple recombination with positive ions (Mitra, 1952). In other words

$$\frac{dn_e}{dt} = q_{eff} - \alpha_{eff} n_e \Sigma n_i^+$$

where q_{eff} and α_{eff} are effective production rate and effective recombination coefficient of electrons, respectively. Assuming that the total positive ion density, Σn_i^+, is equal to the electron density, n_e, we have

$$\frac{dn_e}{dt} = q_{eff} - \alpha_{eff} n_e^2 \tag{1}$$

For positive ions also, instead of a simple recombination with electrons, the process of their loss can be quite complicated. They may undergo charge exchange or ion-atom interchange with neutral molecular gas to form molecular ions, which are then lost by dissociative recombination with electrons. Like free electrons, one can consider that the net loss of a particular type of positive ions of density, n_i^+, is a simple recombination with electrons, namely

$$\frac{dn_i^+}{dt} = q_{eff}^i - \alpha_{eff}^i n_i^+ n_e \tag{2}$$

where q_{eff}^i and α_{eff}^i are the effective production rate and effective recombination coefficient of the positive ions of the ith type. α_{eff}^i is the coefficient which the positive ion of the ith type should have in order to produce the actual loss rate assuming that it disappears by a simple recombination process with electrons. Therefore depending upon the condition of the layer, the effective recombination coefficient of a particular type of positive ion may differ in different ionized layers. Like electrons, the effective recombination coefficient of positive ions gives the overall recombination with electrons and a comparison of their values shows the relative efficiency of different types of positive ions in disappearing in the ionosphere.

As an example, let us find from the above definitions, the effective recombination coefficients of both electrons and positive ions which recombine by the following processes, namely that, in addition to radiative recombination with electrons, positive ions undergo ionic recombination, i.e., the electrons are at first attached to neutral gas particles to form negative ions, which then recombine with positive ions (the negative ions may be lost by photodetachment or collisional detachment).

The rate of density variation of a particular type of positive ion is given by

$$\frac{dn_i^+}{dt} = q_i - (\alpha_{ei} n_i^+ n_e + n_i^+ \Sigma \alpha_{ij} n_j^-)$$

$$= q_i - (\alpha_{ei} n_e + \Sigma \alpha_{ij} n_j^-) n_i^+$$

where α_{ei} and α_{ij} are radiative and ionic recombination coefficients of the ith type of positive ions.

Therefore comparing with Eq. (2), we have

$$q_{eff}^i = q_i$$

$$\alpha_{eff}^i = \left(\alpha_{ei} + \frac{\Sigma \alpha_{ij} n_j^-}{n_e}\right)$$

To find the effective recombination coefficient of electrons, consider the time rate of variation of negative ion and electron densities which are given by

$$\frac{d\Sigma n_i^-}{dt} = n_e \Sigma \beta_i n_i - \Sigma \rho_i n_i^- - n \Sigma \eta_i n_i^- - \Sigma \alpha_{ij} n_i^+ n_j^-$$

and

$$\frac{dn_e}{dt} = \Sigma q_i - n_e \Sigma \beta_i n_i + \Sigma \rho_i n_i^- + n \Sigma \eta_i n_i^- - n_e \Sigma \alpha_{ei} n_i^+$$

where n, β_i, ρ_i, and η_i are neutral particle density, attachment, photodetachment coefficients, respectively. Adding, one obtains

$$\frac{d}{dt}(n_e + \Sigma n_i^-) = \Sigma q_i - \Sigma \alpha_{ij} n_i^+ n_j^- - n_e \Sigma \alpha_{ei} n_i^+$$

Assuming

$$\Sigma n_i^+ = n_e + \Sigma n_i^- = n_e(1+\lambda) \text{ where } \lambda = \Sigma n_i^-/n_e$$

we have

$$\frac{d}{dt}(n_e+\lambda n_e) = \Sigma q_i - (\Sigma\alpha_{ij} n_i^+ n_j^- + n_e\Sigma\alpha_{ei} n_i^+)$$

$$\frac{dn_e}{dt} = \frac{\Sigma q_i}{1+\lambda} - \frac{1}{1+\lambda}(\Sigma\alpha_{ij} n_i^+ n_j^- + n_e\Sigma\alpha_{ei} n_i^+)$$

assuming λ does not vary with time. Therefore, comparing with Eq. (1), we have

$$q_{eff} = \frac{\Sigma q_i}{1+\lambda}$$

and

$$\alpha_{eff} = \frac{1}{(1+\lambda)n_e^2}(\Sigma\alpha_{ij} n_i^+ n_j^- + n_e\Sigma\alpha_{ei} n_i^+)$$

RELATION BETWEEN TWO EFFECTIVE RECOMBINATION COEFFICIENTS

From Eq. (2), we have

$$\frac{d\Sigma n_i^+}{dt} = \Sigma q_{eff}^i - n_e\Sigma\alpha_{eff}^i n_i^+$$

or,

$$\frac{d}{dt}(1-\lambda)n_e = \Sigma q_{eff}^i - n_e\Sigma\alpha_{eff}^i n_i^+$$

If the density of negative ions is small as in E and F regions, we have from Eq. (1)

$$\frac{dn_e}{dt} = \Sigma q_{eff}^i - n_e\Sigma\alpha_{eff}^i n_i^+ = q_{eff} - \alpha_{eff} n_e^2$$

Therefore

$$q_{eff} = \Sigma q^{i}_{eff}$$

$$\alpha_{eff} = \frac{\Sigma\alpha^{i}_{eff}n^{+}_{i}}{n_e} = \frac{\Sigma\alpha^{i}_{eff}n^{+}_{i}n_e}{n_e^2} = \frac{\text{Total loss rate of positive ions}}{n_e^2}$$

Table 5 gives the expressions of the effective electron recombination coefficients and effective positive ion recombination coefficients for different types of recombination processes.

Table 6 shows that the following positive ions have high recombination coefficients: N_2^+ and O^+ ions in E layer, N_2^+, N^+, and O_2^+ ions in F_1, and in F_2 layer O_2^+ and N_2^+. Note that the major ions in ionized layers should have a small effective recombination coefficient as shown in Table 6 (NO^+ and O_2^+ in E layer, NO^+ in F_1, and O^+ in F_2 layer).

The discrepancies between the calculated values of effective recombination coefficients of electrons and their observed values, which may differ by one order or more (Bourdeau, et al., 1966) may be accounted for by the uncertainty in the values of, (1) recombination coefficients and their variations with temperature, and (2) the ion density. Furthermore, while deriving effective recombination coefficients, the flow of ions has not been considered. If the ions flow into the region where the electron density variation with time is considered, it will effectively increase the electron production and if they flow out, the loss term is increased.

TABLE 5

EFFECTIVE PRODUCTION RATES AND EFFECTIVE RECOMBINATION COEFFICIENTS FOR POSITIVE IONS AND ELECTRONS FOR DIFFERENT TYPES OF RECOMBINATIONS

Process	Time Rate of Variation of Electron Density: Equation	Time Rate of Variation of Electron Density: Effective Production Rate and Effective Recombination Coefficient	Time Rate of Variation of Positive Ion Density: Equation	Time Rate of Variation of Positive Ion Density: Effective Production Rate and Effective Recombination Coefficient
I. Radiative and ionic recombination $X_i^+ + e \rightarrow X_i + h\nu$ $Y_j + e \rightarrow Y_j^- + h\nu$ $X_i^+ + Y_j^- \rightarrow X_i + Y_j$	$\frac{dn_e}{dt} = \frac{\Sigma q_i}{1+\lambda} - \frac{1}{1+\lambda}(\Sigma\alpha_{ij}n_i^+n_j^- + n_e\Sigma\alpha_{ei}n_i^+)$	$q_{eff} = \frac{\Sigma q_i}{1+\lambda}$ $\alpha_{eff} = \frac{1}{(1+\lambda)n_e^2}(\Sigma\alpha_{ij}n_i^+n_j^- + n_e\Sigma\alpha_{ei}n_i^+)$	$\frac{dn_i^+}{dt} = q_i - n_i^+(\Sigma\alpha_{ij}n_j^- + \alpha_{ei}n_e)$	$q_{eff}^i = q_i$ $\alpha_{eff}^i = \left(\frac{\Sigma\alpha_{ij}n_j^-}{n_e} + \alpha_{ei}\right)$
II. Dissociative recombination $(XY^+)_i + e \rightarrow X_i + Y_i$	$\frac{dn_e}{dt} = \Sigma q_i - n_e\Sigma\alpha_D^i n_i^+$	$q_{eff} = \Sigma q_i$ $\alpha_{eff} = \frac{\Sigma\alpha_D^i n_i^+}{n_e}$	$\frac{dn_i^+}{dt} = q_i - \alpha_D^i n_i^+ n_e$	$q_{eff}^i = q_i$ $\alpha_{eff}^i = \alpha_D^i$
III. Charge exchange followed by dissociative recombination $X_i^+ + (YZ)_j \rightarrow X_i + (YZ^+)_j$ $(YZ^+)_j + e \rightarrow Y_j + Z_j$	$\frac{dn_e}{dt} = \Sigma q_i - n_e\Sigma\alpha_D^j n(YZ^+)_j$	$q_{eff} = \Sigma q_i$ $\alpha_{eff} = \frac{\Sigma\alpha_D^j n(YZ^+)_j}{n_e}$	$\frac{dn_{i\,a,m}^+}{dt} = q_i - n_e\Sigma\alpha_D^i n_{i\,m}^+$ where a,m refer atomic and molecular ions respectively	$q_{eff}^i = q_i$ $\alpha_{eff}^i = \frac{\Sigma\alpha_D^i n_{i\,m}^+}{n_{i\,a,m}^+}$

TABLE 6

EFFECTIVE RECOMBINATION COEFFICIENT OF POSITIVE IONS AND ELECTRONS

Altitude (km)	Effective Recombination Coefficients ($cm^3 sec^{-1}$) of Positive Ions and Electrons					
	O^+	O_2^+	N^+	N_2^+	NO^+	n_e
110	1.9×10^{-5}	5.0×10^{-7}	9.4×10^{-6}	2.0×10^{-5}	3.7×10^{-7}	4.4×10^{-7}
180	1.6×10^{-7}	1.3×10^{-6}	3.8×10^{-6}	6.0×10^{-6}	6.4×10^{-8}	3.2×10^{-7}
260	3.8×10^{-9}	1.7×10^{-7}	3.9×10^{-8}	2.2×10^{-6}	4.5×10^{-8}	8.8×10^{-9}

5. DIFFUSION OF POSITIVE IONS

The diffusion of positive ions through the atmosphere can be obtained from the altitude distribution of total positive ion density by considering an electron-positive ion plasma moving as a minor constituent through the neutral gas (the electrostatic force between them enables the plasma to move as a whole). Writing the continuity equation, namely

$$\frac{d\Sigma n_i^+}{dt} = \Sigma q_i - \Sigma L_i - \text{div}(\Sigma n_i^+ v)$$

where

Σq_i - rate of production of all positive ions

ΣL_i - rate of their losses

Σn_i^+ - density of total positive ions having a mean drift v,

it can be shown that (Ratcliffe, 1960)

$$-\text{div}(\Sigma n_i^+ v) = -\frac{d(w\Sigma n_i^+)}{dz} = \frac{dD}{dz}\left(\frac{d\Sigma n_i^+}{dz} + \frac{\Sigma n_i^+}{2H}\right)$$

$$+ D\left(\frac{d^2\Sigma n_i^+}{dz^2} + \frac{1}{2H}\frac{d\Sigma n_i^+}{dz}\right)$$

Neglecting the presence of negative ions,

$$-\frac{d(w\Sigma n_i^+)}{dz} = \frac{dD}{dz}\left(\frac{dn_e}{dz} + \frac{n_e}{2H}\right) + D\left(\frac{d^2 n_e}{dz^2} + \frac{1}{2H}\frac{dn_e}{dz}\right)$$

where

w - upward component of v

H - scale height of electron-ion mixture

D - ambipolar diffusion coefficient of ions = $\frac{9\text{x}10^{16}T^{1/2}}{n}\sin^2 I$ (Nawrocki, *et al.*, 1963) where n is the density of neutral gas, I, the inclination of the earth's magnetic field and T, the ion temperature.

Assuming that the ions move vertically so that sin I = 1 (actually this is true at magnetic poles), $d(w\Sigma n_i^+)/dz$ is calculated from the curve relating the variation of total positive ion density with altitude (Fig. 1) and is shown in Table 7. The negative sign at 270 km is due to the change of curvature of the curve from 250 km. It is to be seen that the diffusion of the positive ions is very small at low altitudes and at 270 km becomes only 1-2% of the total loss rate. Therefore, in agreement with Sagalyn, et al. (1963), even at the altitude of F2 peak, the diffusion of positive ions is unimportant.

TABLE 7

DIFFUSION OF POSITIVE IONS

Altitude (km)	$-\frac{d(w\Sigma n_i^+)}{dz}$ (sec^{-1} cm^{-3})
150	3.2
180	8.7
210	2.0×10^1
240	2.8×10^1
270	-2.0×10^1

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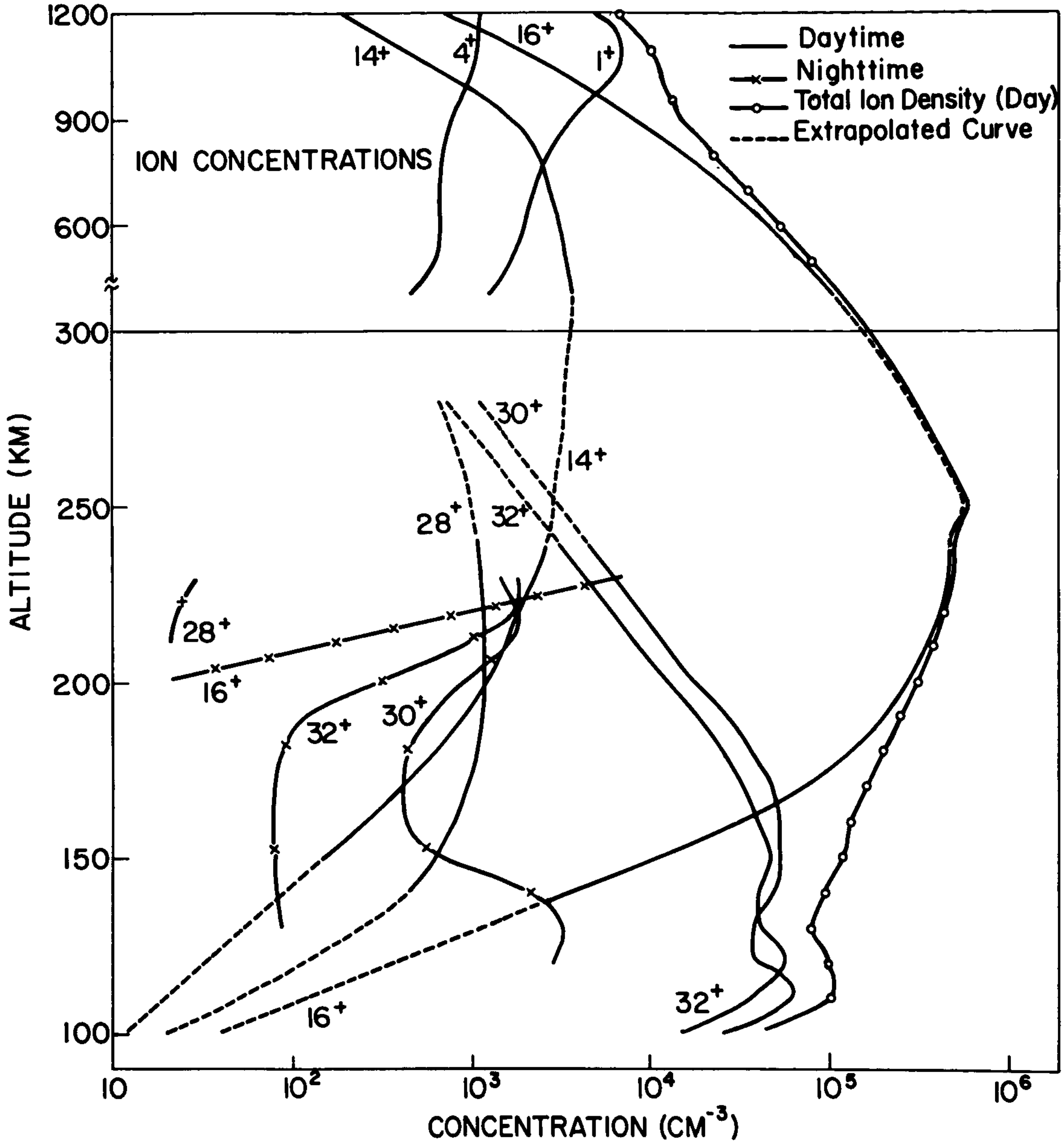

Fig. 1. Day and night time altitude variations of positive ions during the last solar minimum activity period averaged from observations made by different investigators. Note the low ion densities of O^+ and N_2^+ ions, and the rapid fall of O^+ ions at 230 km with decreasing altitude at night.

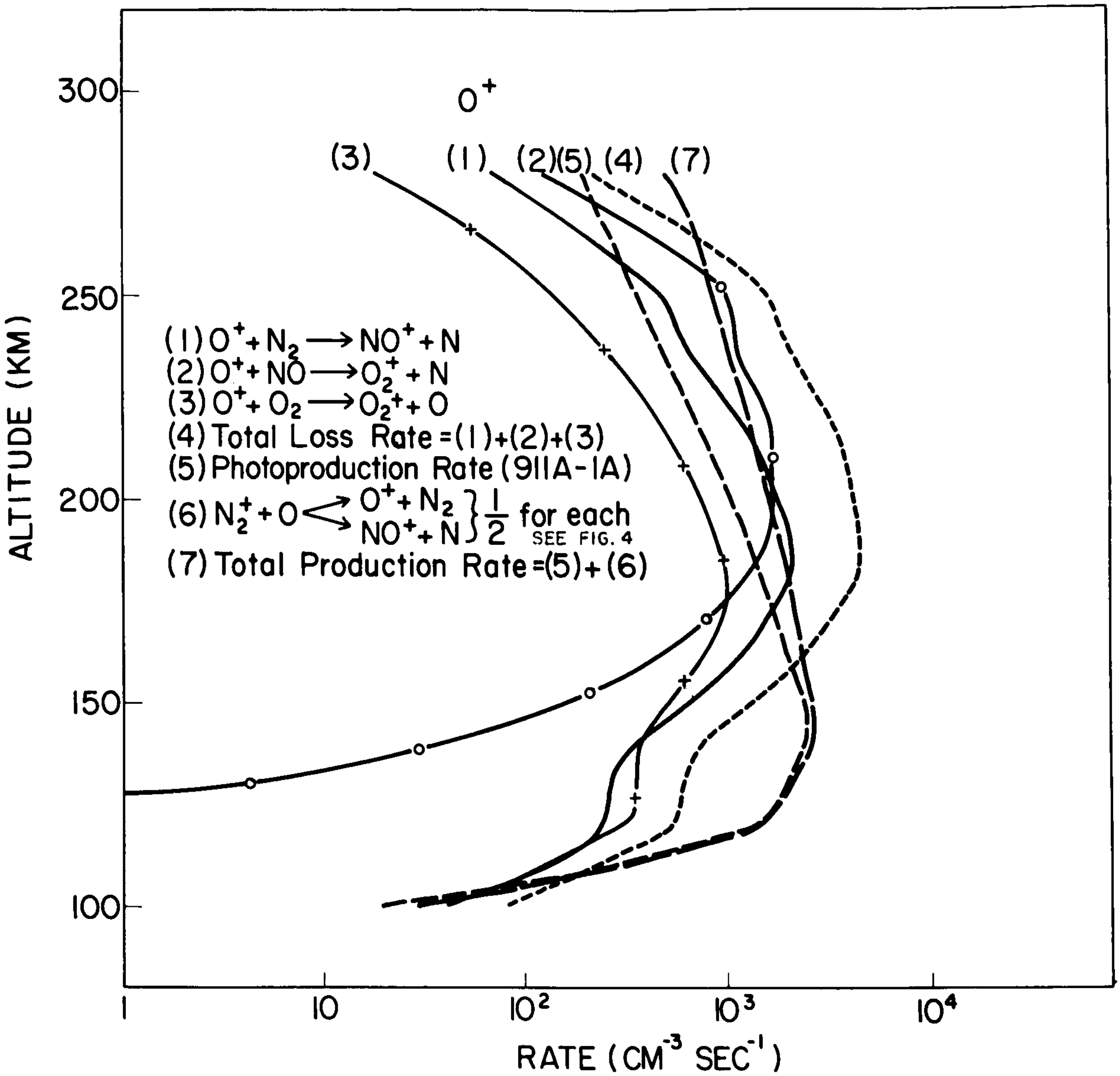

Fig. 2. Production (by photons and exchange processes) and loss rates of O^+ ions for 100-280 km.

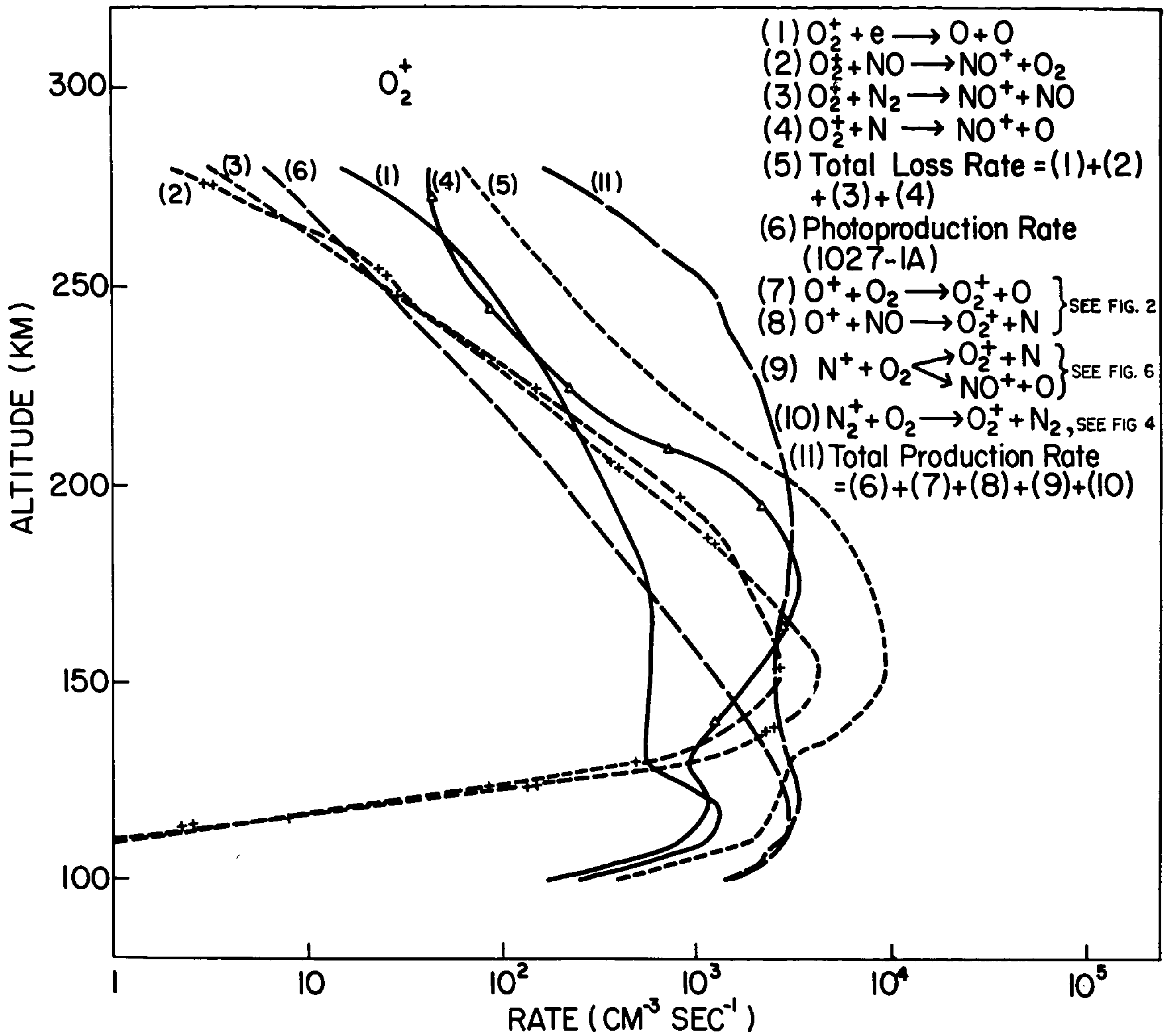

Fig. 3. Production (by photons and exchange processes) and loss rates of O_2^+ ions for 100-280 km.

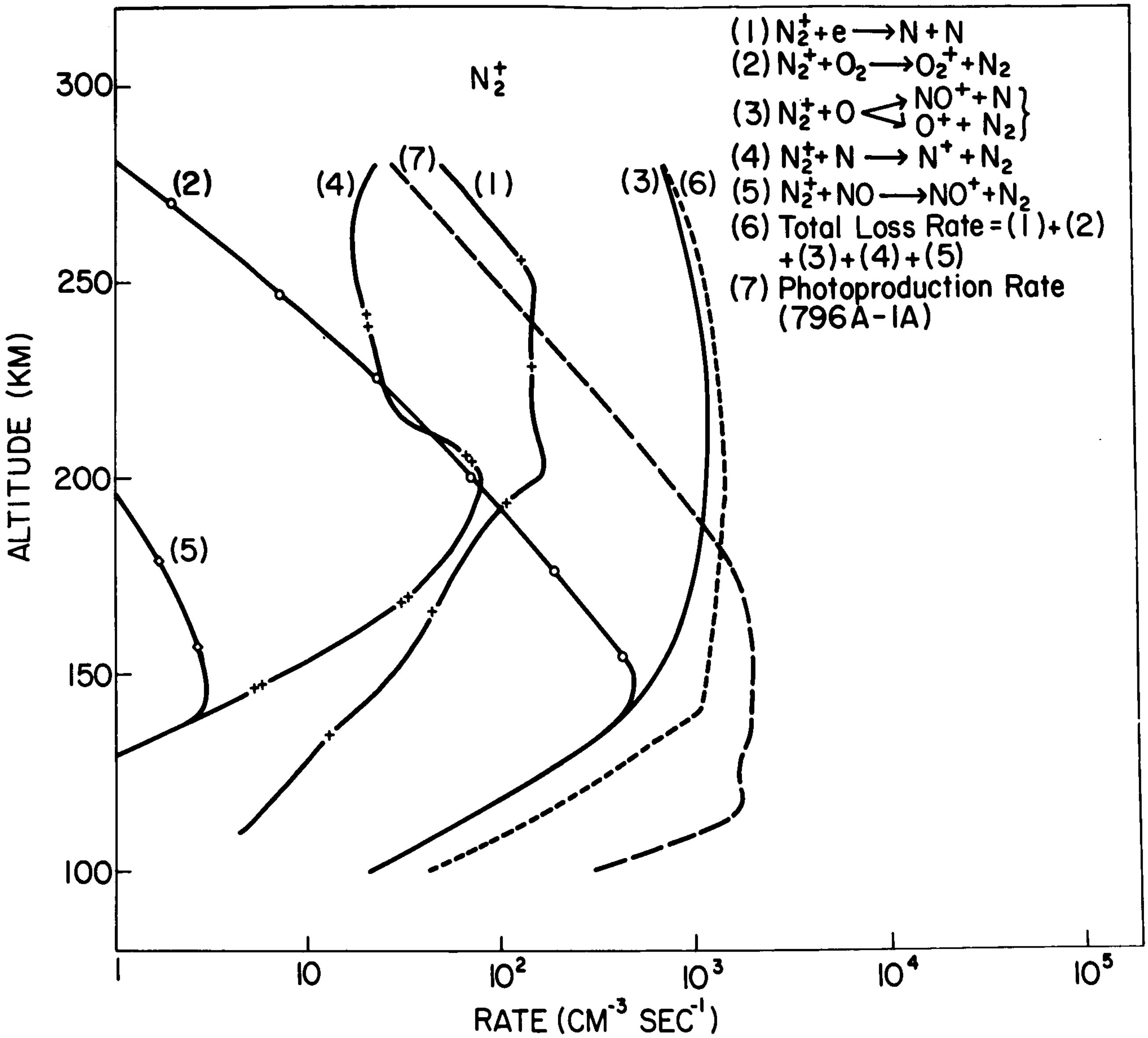

Fig. 4. Photoproduction and loss rates of N_2^+ ions for 100-280 km.

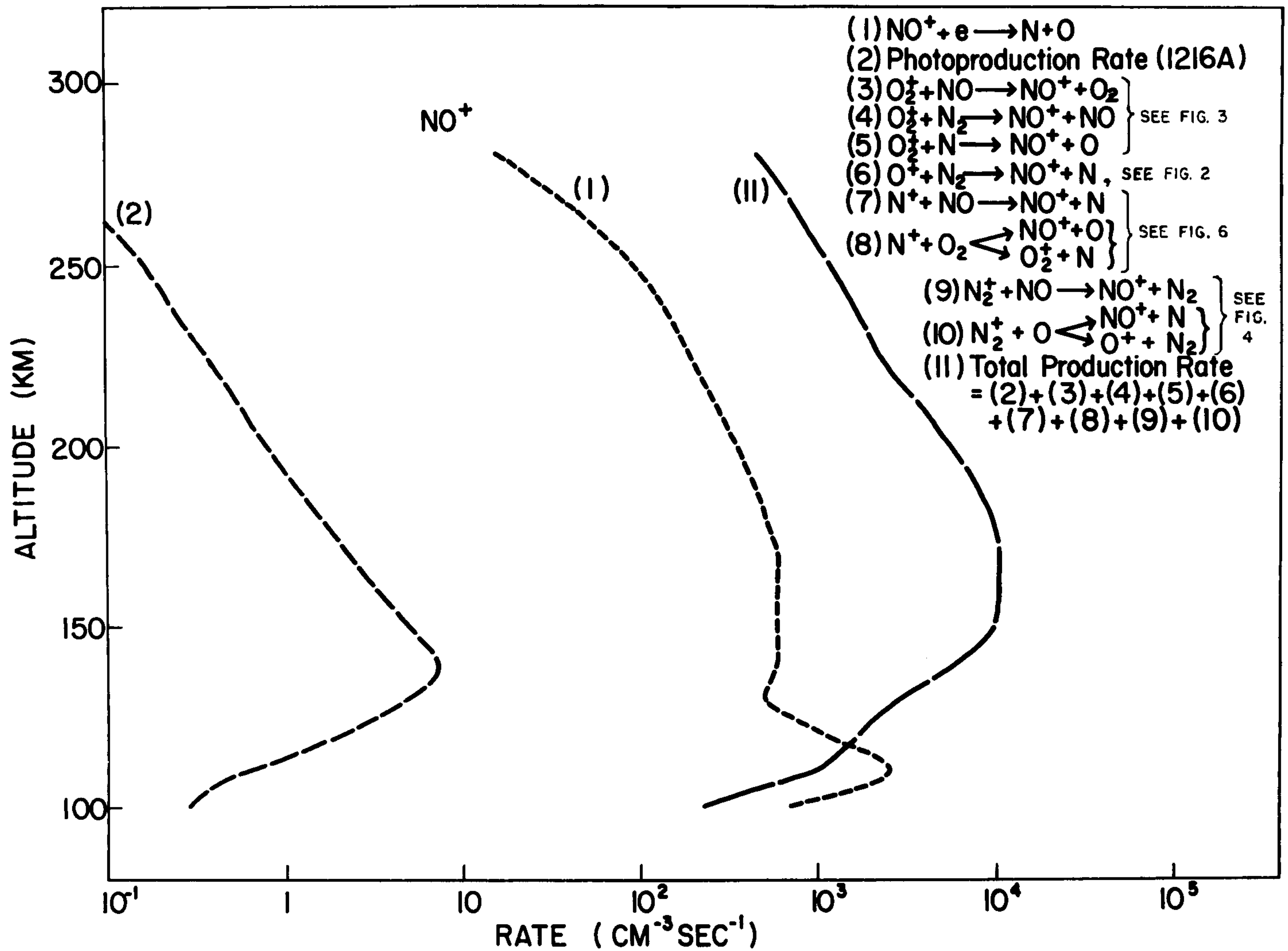

Fig. 5. Production (by Lyman-α and exchange processes) and loss (by dissociative recombination with electrons) rates of NO^+ ions for 100-280 km.

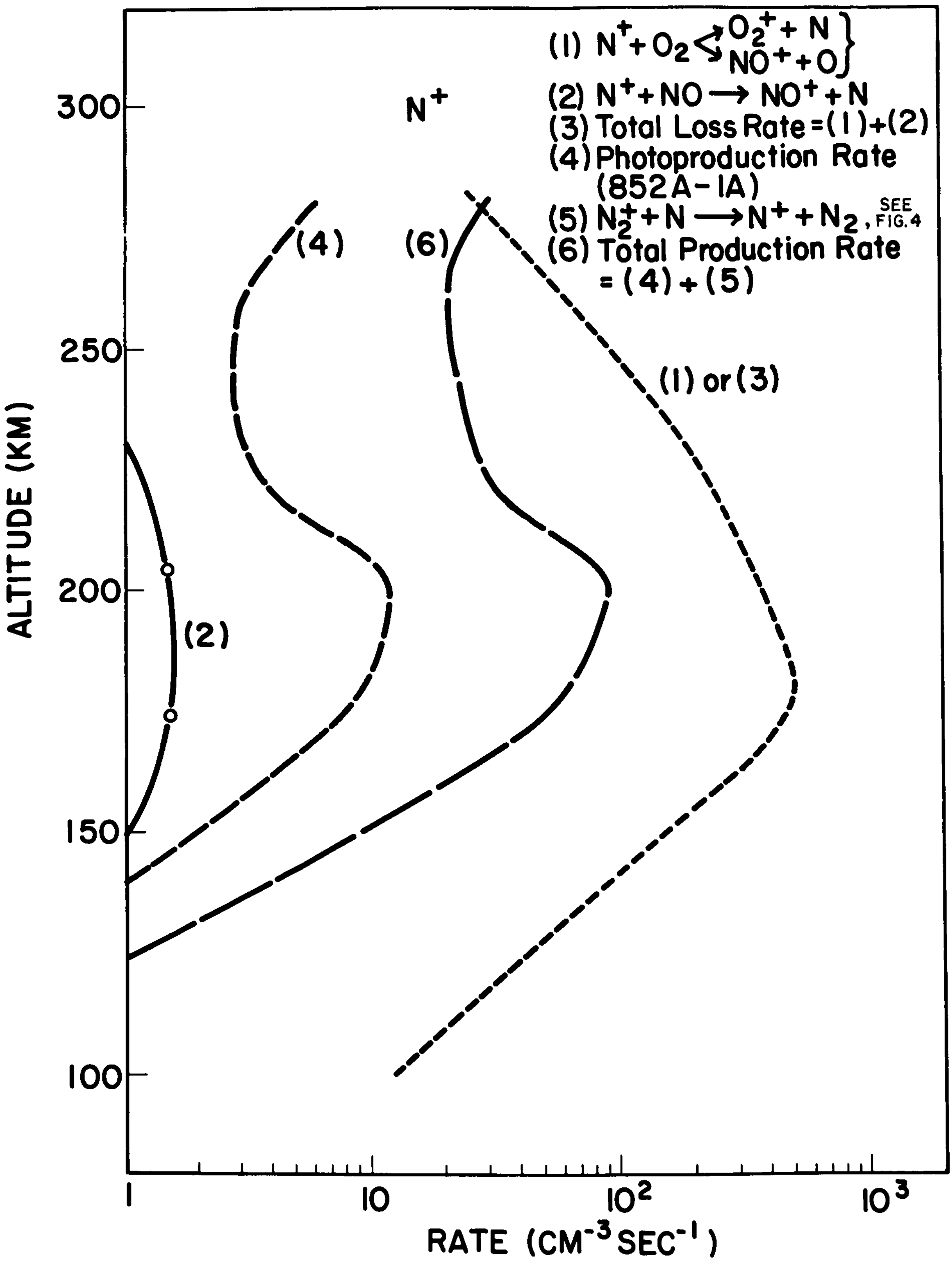

Fig. 6. Production (by photons and exchange processes) and loss rates of N^+ ions for 100-280 km.

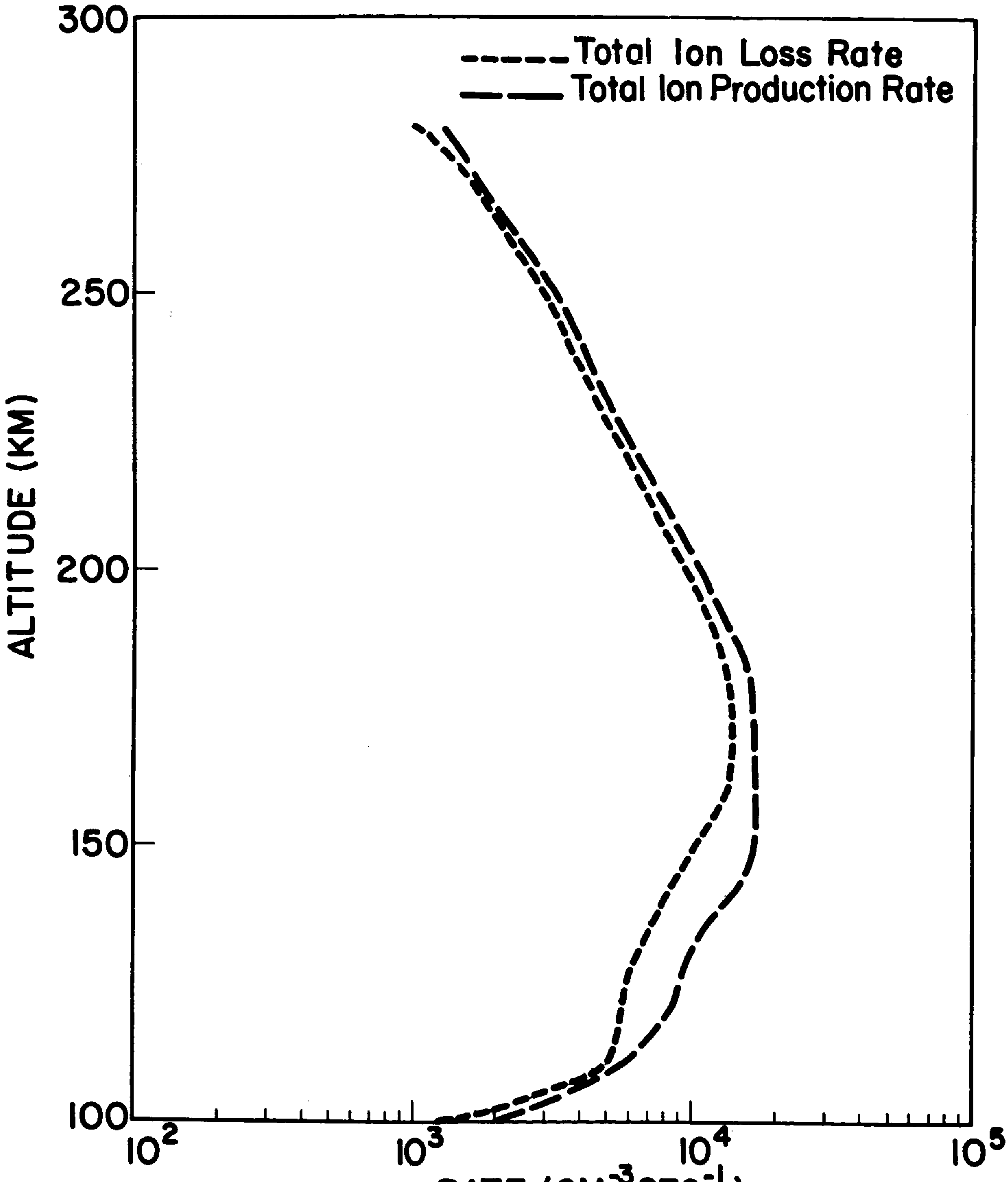

Fig. 7. Total production and loss rates of all positive ions for 100-280 km.